NSTX

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Novel Alfvén eigenmode structure measurements in NSTX via reflectometry*

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and the NSTX Research Team

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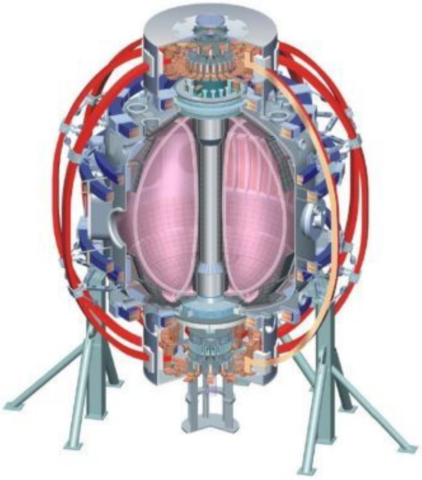

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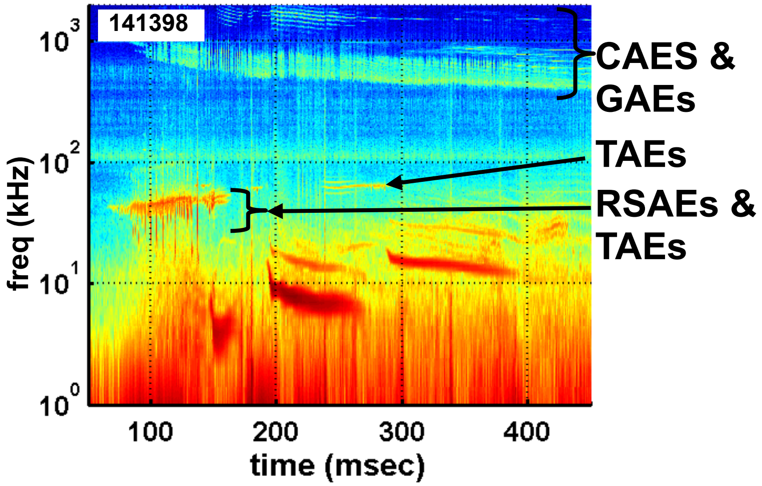
Summary

- Motivation: Alfvén eigenmodes (AE) can impact plasma performance
  - Low Frequency AEs (TAE & RSAE), $f <\sim 200$ kHz ⇒ fast-ion transport
  - High Frequency AEs (CAE & GAE), $f >\sim 400$ kHz ⇒ correlated with enhanced χ_e
- AE structure measured via 16-channel reflectometer array, $n_0 \sim 1 - 7 \times 10^{19}$ m^{-3} (30 – 75 GHz)
- High frequency AE structure measured in core of beam heat-heated H-mode plasmas ⇒ identified as CAEs and GAEs
- CAEs strongly core localized ⇒ may cause thermal electron transport
  - GAE activity correlates with enhanced electron thermal transport; proposed as cause [D. Stutman *et al*., PRL **102** 115002 (2009); K. Tritz, APS DPP 2010 Invited PI2.2]
  - CAEs share key GAE characteristics: core localization & frequency
- TAE structure measured (amplitude and phase) with high resolution ⇒ strong radial phase variation across plasma ($\Delta\phi \sim \pi/2$)
  - indicates radial propagation
- TAE phase variation indicates non-ideal physics
  - inconsistent with ideal MHD
  - M3D-K simulation implicates coupling with fast-ions

Motivation: Alfvén eigenmode structure measurement promotes better understanding of plasma performance

- NSTX plasmas feature rich spectrum of Alfvén eigenmodes
  - Low frequency AEs (f < ~ 200 kHz): Toroidicity-induced (TAE) & Reversed shear (RSAE)
  - High frequency AEs (f > ~ 400 kHz): Compressional (CAE) & Global (GAE)

δb spectrum of typical beam-heated NSTX plasma

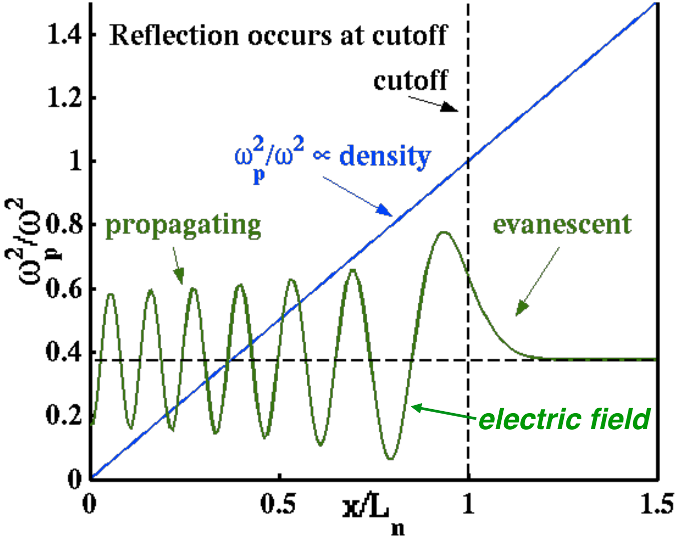


- Alfvén eigenmodes (AE) play critical role in many aspects of plasma performance
  - Low frequency AEs cause fast-ion transport and loss:
    - change equilibrium sources (momentum, energy …)
    - damage plasma facing components
  - High frequency AE activity correlates with enhanced χ_e in core of H-mode beam heated plasmas

    D. Stutman *et al.*, PRL **102** 115002 (2009); K. Tritz, APS DPP 2010 Invited PI2.2
- Mode δn structure routinely measured in NSTX via fixed-frequency reflectometer radial array
  - 16 channels, $n_0 \sim 1 - 7 \times 10^{19}$ m^{-3} (30 – 75 GHz)

Reflectometers measure local density fluctuation in plasma

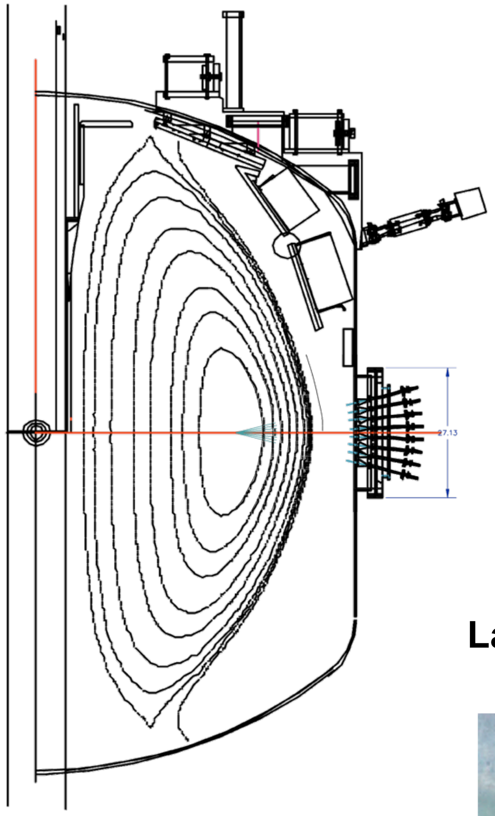
- Microwaves propagate to "cutoff" layer, where density high enough for reflection ($\omega_p = \omega$)
  - Dispersion relation of "ordinary mode" microwaves: $\omega^2 = \omega_p^2 + c^2k^2$, ω_p^2 proportional to density ($\omega_p^2 = e^2n_0/\varepsilon_0 m_e$)
  - $k \rightarrow 0$ as $\omega \rightarrow \omega_p$, microwaves reflect at $k = 0$
- Reflectometer measures path length changes of microwaves reflected from plasma
  - phase between reflected and launched waves changes ($\delta\phi$)
- Wave propagation controlled by density
  - for large scale modes $\delta n/n_0 \sim \delta\phi/(2k_{vac}L_n)$, $L_n = n_0/|\nabla n_0|$



Microwave ("O-mode") propagation

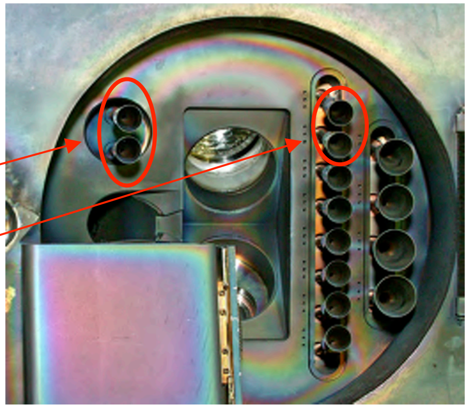
Reflectometers provide radial array of measurements

NSTX cross-section



- Two arrays: “Q-band” & “V-band”
  - –Q-band: 30, 32.5, 35, 37.5, 42.5, 45, 47.5 & 50 GHz
  - –V-band: 55, 57.5, 60, 62.5, 67.5, 70, 72.5 & 75 GHz
- Arrays closely spaced (separated ~ 10° toroidal)
- Single launch and receive horn for each array
- Horns oriented perpendicular to flux surfaces ⇒ frequency array = radial array
- Cutoffs span large radial range in high density plasmas (n_0 ~ 1 – 7 x 10^{19} m^{-3})

Launch and Receive Horns (Interior View)

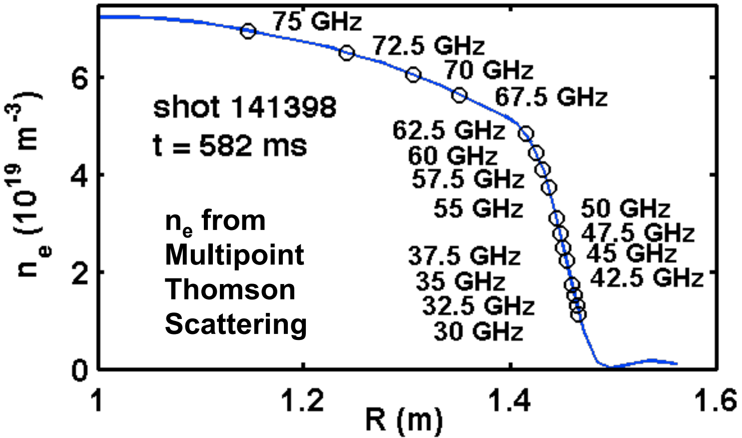


30-50 GHz

55-75 GHz

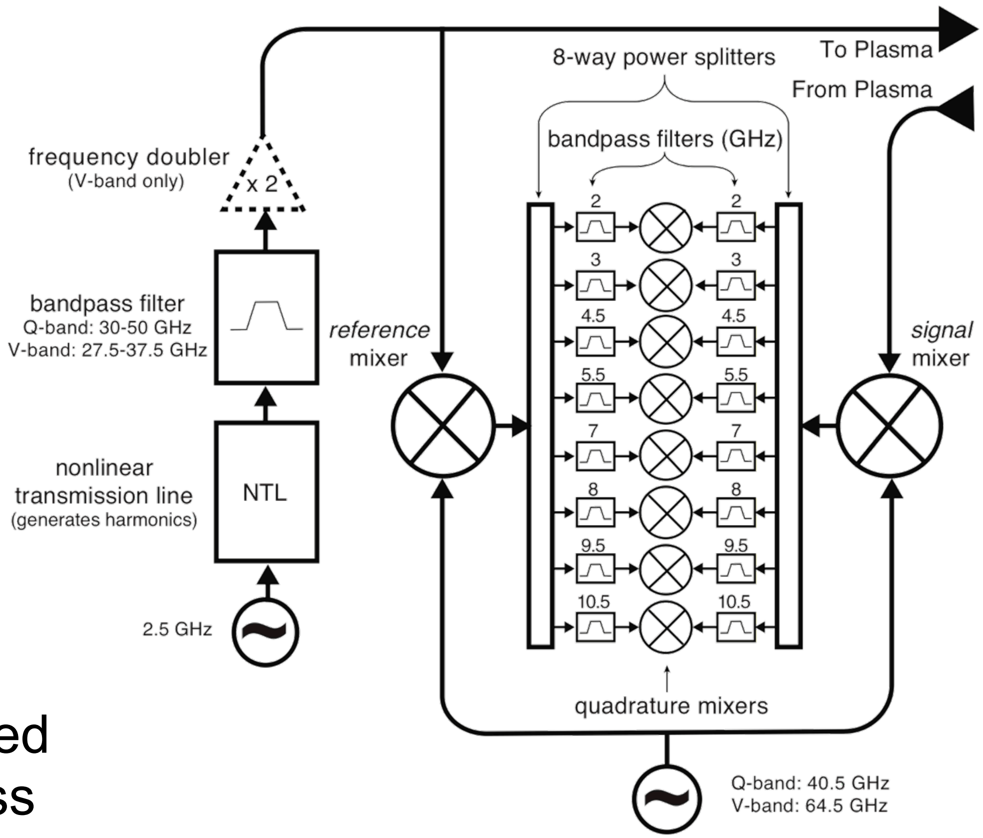
(not shown: horns modified to optimize for frequency range)

n_e and O-mode cutoff locations



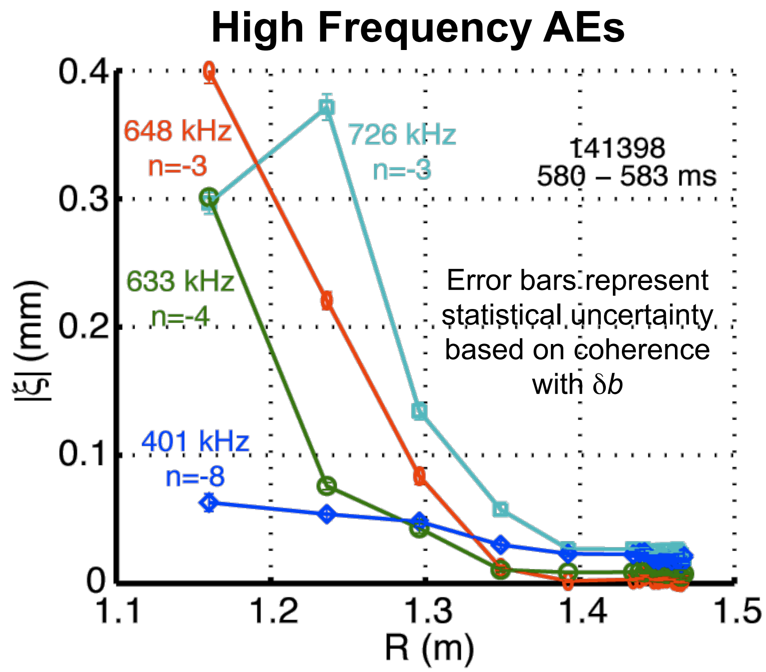
Microwave circuit exploits nonlinear transmission line

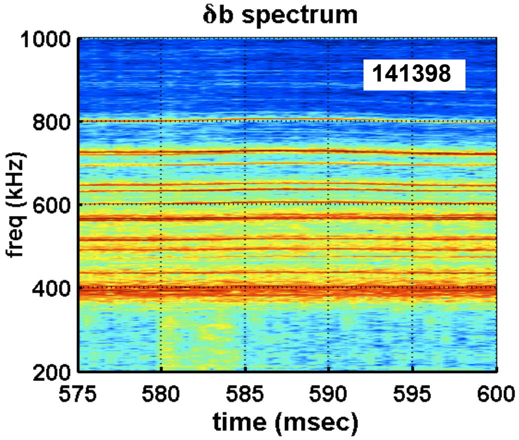
- 2.5 GHz source + nonlinear transmission line ⇒ harmonics up to 50 GHz
- Bandpass filter selects frequency range
  - Q-band: 30 – 50 GHz
  - V-band: 27.5 – 37.5GHz (frequencies doubled after filter)
- Frequencies downshifted to <= 10.5 GHz for processing
- Individual freq. isolated & processed via 8-way power splitters, bandpass filters & quadrature mixers

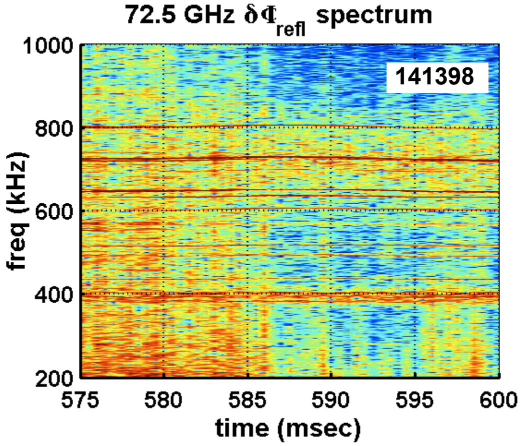


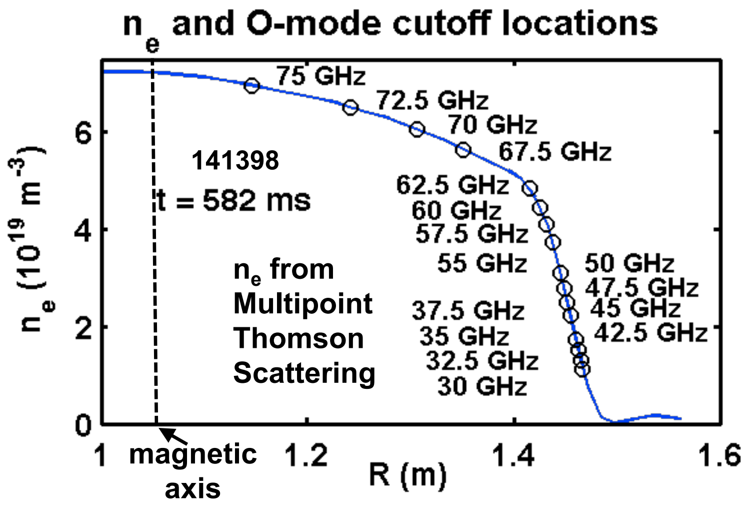
High Frequency AE structure measured in core of H-mode beam heated plasma*

- High frequency AE structures measured with 16 channels in 6 MW beam-heated H-mode plasma
- Observed modes fall in two categories:
  - Small amplitude + broad structure, *f* < ~ 600 kHz, n = -7 & -8 (e.g. *f* = 401 kHz on right)
  - Large amplitude + strongly core localized, *f* > ~ 600 kHz, n = -3, -4 & -5 (e.g. *f* = 633, 648 and 726 kHz on right)









***N A Crocker et al. PPCF 53 105001 (2011)**

Modes can be identified as CAEs or GAEs via mode number and frequency evolution

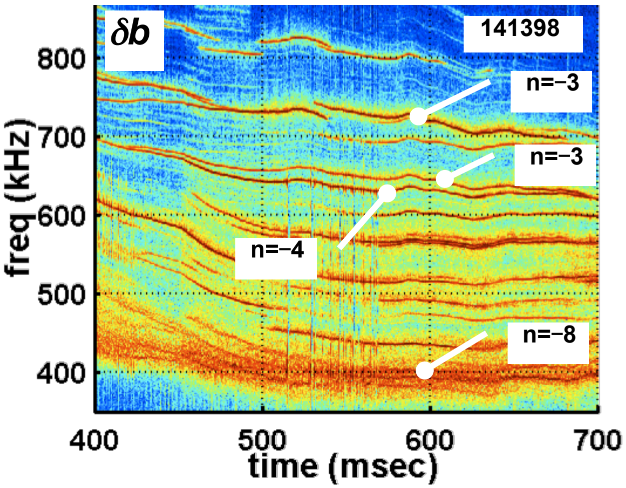
- GAE and CAE frequency have distinctly different sensitivity to equilibrium
  - Mode frequency evolution can be compared to local dispersion relations:

$$f_{CAE} \sim \frac{kv_A}{2\pi} + nf_{ROT}, k \sim \left[\left(\frac{n}{R}\right)^2 + \left(\frac{m}{r}\right)^2 + \delta_r^{-2}\right]^{1/2}$$

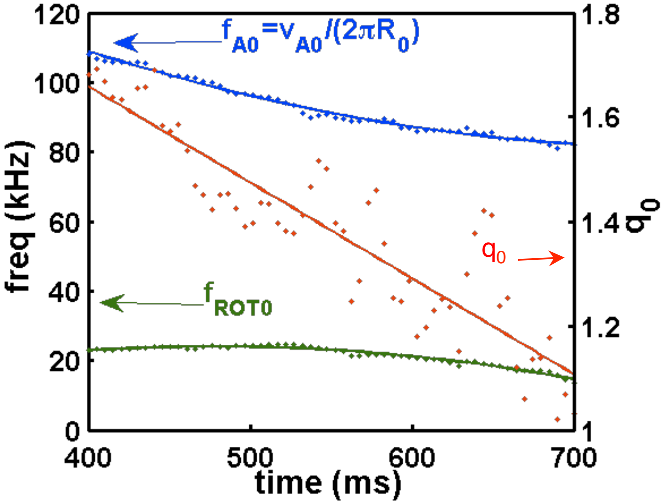
$$f_{GAE} = \frac{k_\parallel v_A}{2\pi} + nf_{ROT}, k_\parallel \approx \frac{1}{R}\left|\frac{m}{q} - n\right|$$

- Toroidal mode numbers (n) measured via 10 B-dot coils in toroidally distributed array
- Equilibrium trends known from measurement:
  - q_0 and B_0 from equilibrium reconstruction using magnetic field pitch from Motional Start Effect
  - n_{e0} measured via Multipoint Thomson Scattering
  - Alfvén velocity, $v_{A0} = B_0/(\mu_0\rho_0)^{½}$
    - $\rho_0=m_Dn_{e0},$ m_D=Deuterium mass
  - Toroidal rotation frequency, f_{ROT0}, from Charge Exchange Recombination Spectroscopy

AE frequency evolution



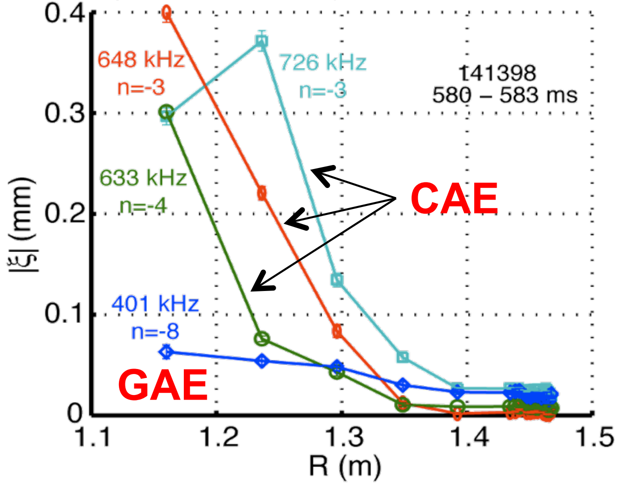
Equilibrium trends



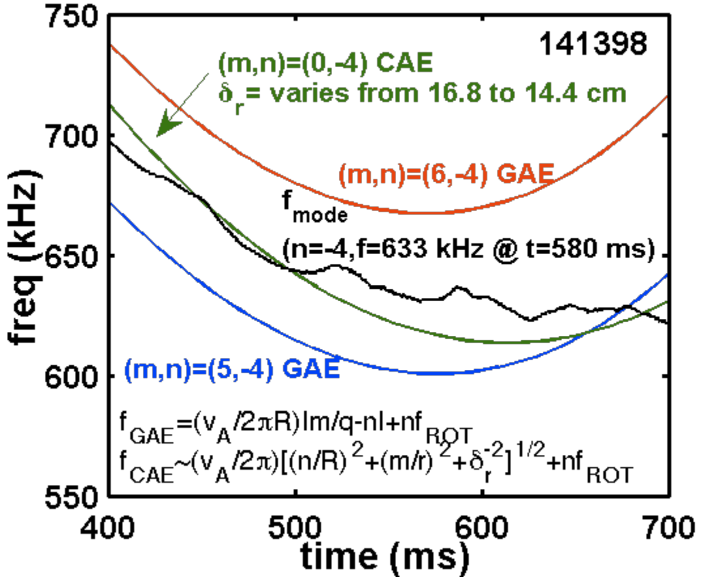
Frequency sensitivity to q_0 key in distinguishing CAEs from GAEs

- Expected GAE frequency evolution sensitive to m/q_0 if $|m| >> 1$
  - q_0 varies substantially (1.7 – 1.1) over t = 400 – 700 ms
- Modes with $f <\sim 600$ kHz, $n = -7$ & -8 Identified as GAEs
  - $|n| >> 1 \Rightarrow f(t) \sim f_{GAE}(t)$ if low $|m|$
- Modes with $f >\sim 600$ kHz, $n = -5, -4$ & -3 Identified as CAEs
  - $f(t)$ consistent with $f_{CAE}(t)$
    - Assume low $|m|$: m =0,1
    - Assume slowly varying plausible radial scale (from mode structure): $\delta_r \sim 15 – 25$ cm
  - $f(t)$ NOT consistent with $f_{GAE}(t)$: low $|n|$, high f $\Rightarrow$ high $|m|$ $\Rightarrow$ strong q_0 sensitivity

High Frequency AEs Identified



Example of identification analysis:
f_{mode} = 633 kHz @ t = 580 ms



Identification of core-localized CAEs motivates future investigation of CAEs as possible of cause enhanced χ_e

- GAEs proposed as cause enhanced χ_e in core of NSTX beam-heated H-mode plasmas
    - D. Stutman *et al.*, PRL **102** 115002 (2009)
    - K. Tritz, APS DPP 2010 Invited PI2.2
    - High frequency AE activity, identified as GAEs, correlates with enhanced χ_e in core
    - GAE frequency ~ electron orbit frequencies ⇒ resonant orbit modification
    - GAE core localization expected ⇒ active in region of enhanced χ_e
- Modes identified as CAEs can also modify electron orbits in core
    - CAEs shown to be core localized, with frequencies similar to GAEs
    - CAEs stronger & more core localized than GAEs ⇒ more impact on electrons than GAEs?

D. Stutman et al., PRL 102 115002 (2009)

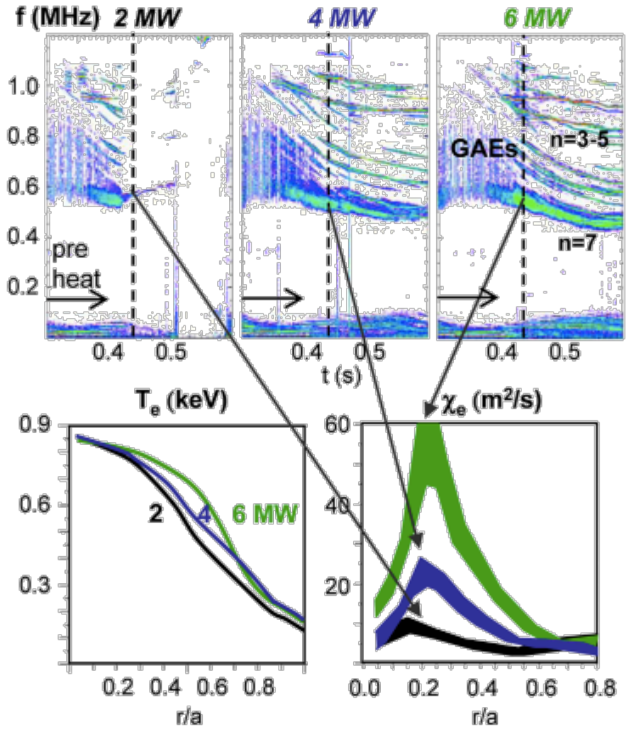
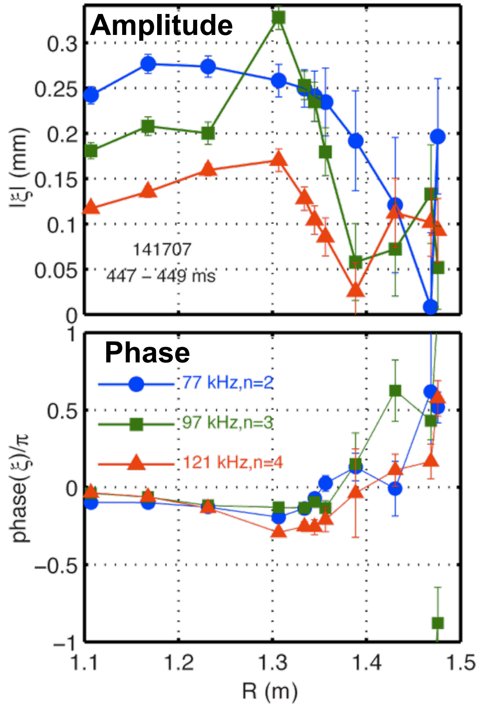


FIG. 3 (color online). Correlation between GAE activity, T_e flattening, and central χ_e increase in NSTX H modes heated by 2, 4, and 6 MW neutral beam, at $t \sim 0.44$ s. Within the uncertainties, the q, n_e, and $\omega_{E\times B}$ profiles are the same in all discharges at the time of the transport correlation [13].

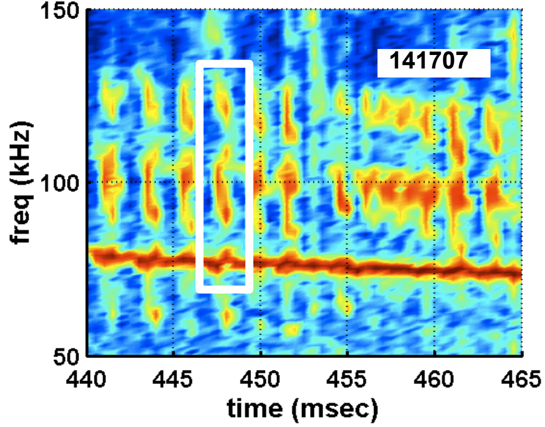
TAE structure measured with high spatial resolution

- TAE structure (amplitude and phase) measured across plasma at 12 locations near midplane
  N A Crocker *et al*. PPCF **53** 105001 (2011)
- Strong radial phase variation ($\Delta\Phi \sim \pi/2$) observed
  - Indicates radial propagation
- Measurement advances campaign to validate M3D-K code
  - High resolution strengthens comparison

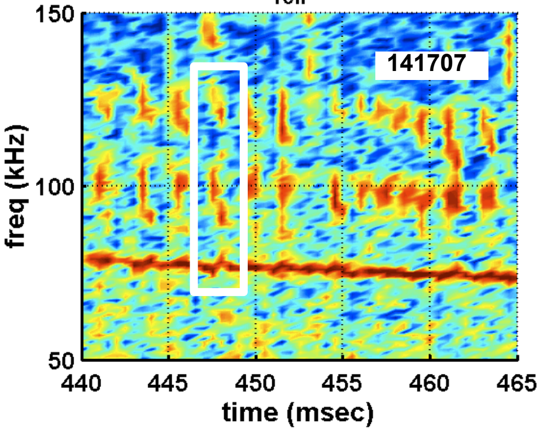
TAE structure



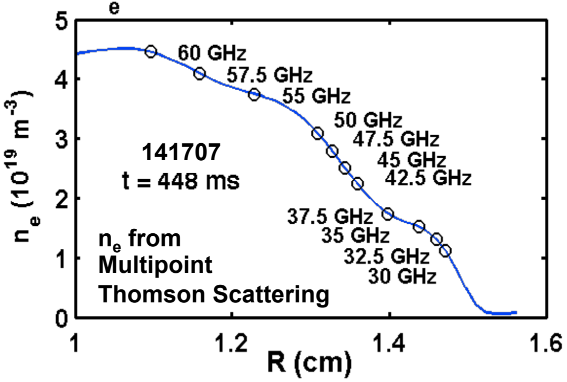
δb spectrum



60 GHz $\delta\Phi_{refl}$ spectrum

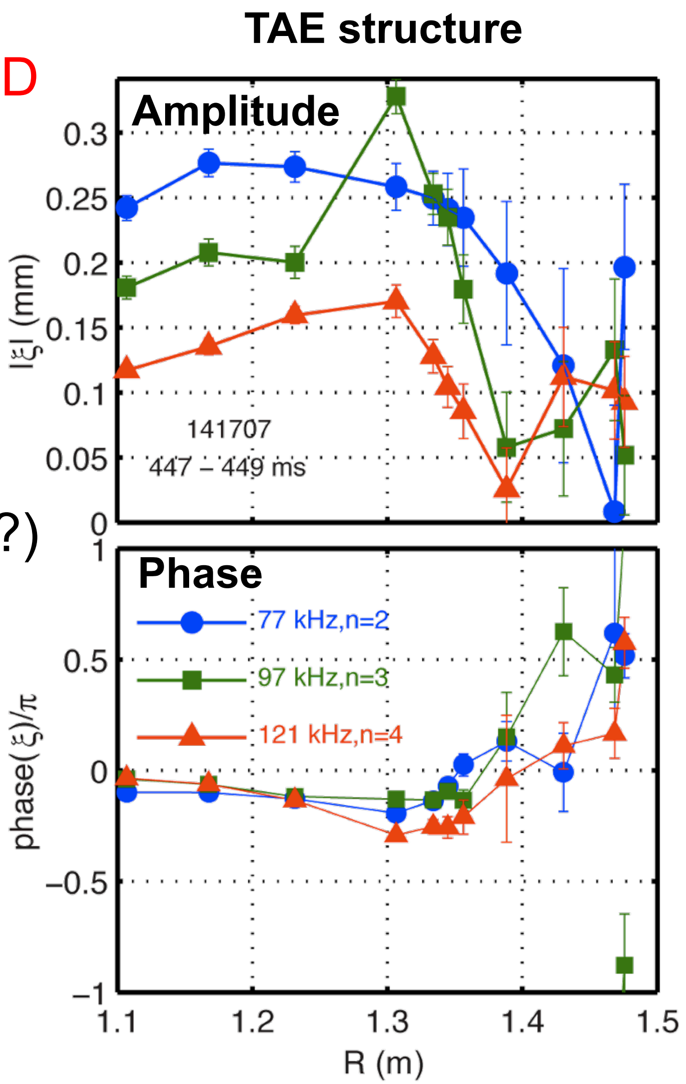


n_e and O-mode cutoff locations



Strong radial phase variation of TAEs indicates non-ideal MHD physics*

- Radial phase variation inconsistent with ideal MHD
  - Measurements approx. in midplane
  - Plasma up-down symmetric ⇒ ideal MHD predicts real-valued eigenmode in midplane (phase = 0 or 180°)
  - Caveat: effect of plasma rotation not clear from theory
- Coupling to fast-ions (and other non-ideal effects?) may explain phase variation
  - Radial phase variation observed for RSAEs in DIII-D [BJ Tobias *et al*. PRL **106** 075003 (2011)]
    - Comparison with TAE/FL code implicates coupling with fast-ions
  - M3D-K simulation NSTX included fast-ion & shows similar phase variation

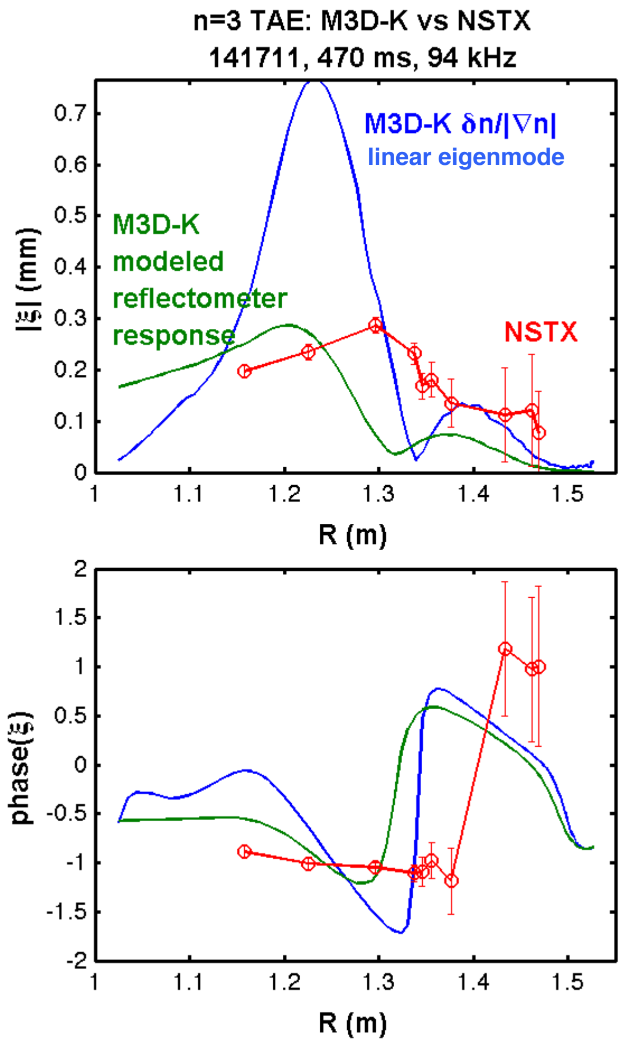

TAE structure

Observed TAE structure similar to M3D-K linear eigenmode prediction

- M3D-K solves for TAE eigenmode in NSTX plasma
  - initial value code
  - MHD plasma coupled to kinetically treated energetic ions
- Reflectometer response (ξ) modeled for M3D-K δn (i.e. "synthetic diagnostic")
  - WKB approximation for path length (L) used:

$$L = L_0 + \xi = \int_{edge}^{\omega_P^2(R)=\omega^2} \sqrt{1-\omega_P^2(R)/\omega^2}\, dR$$

- M3D-K structure [|ξ| & phase(ξ)] similar to NSTX, but shifted radially inward ~ 7 cm
  - further work needed to understand shift



Conclusions

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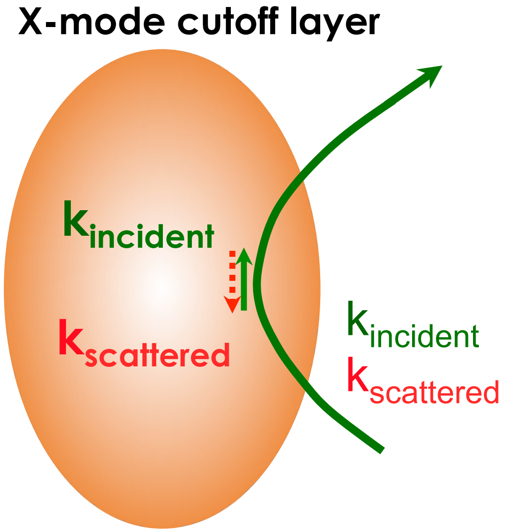
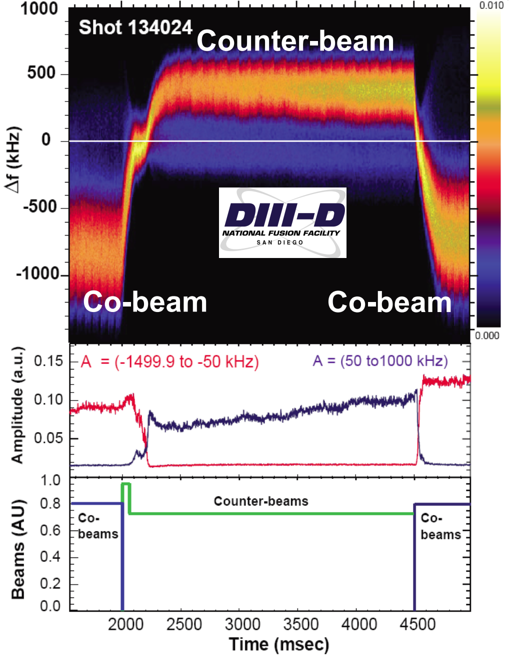
Doppler backscattering (DBS): Determines equilibrium E_r & oscillating flows associated with GAMs & Alfven modes

- DBS locally measures scattering from intermediate scale turbulence
  - Doppler shift provides information on local turbulent flow. Equilibrium & oscillating flows are imprinted onto Doppler shift
  - Allows determination of radial profile of oscillating electric fields of GAMs, Alfven waves, etc.



Quadrature data for co- and counter beams



DBS phase analysis of GAMs & Alfven modes